Fermilab

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PROPERTIES OF THE PROTON DEPARTMENT CURRENT DIGITIZER AND GATE MODULE

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INTRODUCTION

The offset and maintenance problems associated with analog integrators being used with SEM'S to measure beam intensity are attributable to gating low level currents and having to reset an analog device. Both of these requirements become trivial when a current digitizer is used because they can be done digitally. A current or charge digitizer produces a pulse per unit of charge ($\hat{q}$) entering the device. Hence, the output frequency is proportional to the input current. The Proton Department Instrumentation Group has built a NIM Packaged negative current digitizer using the circuit concepts originally put forth by Bob Shafer of Research Services (TM391 and 391A). The primary differences in the Proton version is the removal of the calibration dependency on the NIM power supply, the addition of temperature compensation, and selecting the appropriate trade-offs to make it more adaptable for use with SEM'S.

In order to obtain a scale factor (S.F.) of 10^8 protons/count, a unit charge per pulse ($\hat{q}$) of the Digitizer would have to be less than 3.62 pc/pulse i.e., the lowest SEM gain (S. G.) observed thus far has been 3.62 pc/10^8 protons. The Digitizer has been operated successfully with a $\hat{q}$ of 2 pc/pulse, however, it does not appear advantageous to do so for use with SEM'S. Although the $\hat{q}$ can be adjusted to match the gain of the SEM, thereby, tailoring a given module to a given SEM, a major goal of the design was not to have tailored modules. The method by which this is accomplished is to standardize on a specific $\hat{q}$ of 3 pc/pulse and digitally scale the pulses from the Current Digitizer with a second module called the Gate Module. In addition to gating the pulses from the digitizer, the Gate Module essentially multiplies the number of input pulses by a three digit multiplier (M) in the range of 0.001 to 0.999 before outputting them to a scaler. The multiplier (M) is selectable with PC board mounted HEX switches from the rear of the NIM Module. Figure (1) is a basic block diagram of the system and shows the relationship of the various gains of each part of the system. It can be seen that for a SEM which produces 3.62 pc/10^8 protons, $\hat{q}$ = 3 pc/pulse, and M = 0.829, a scale factor of 1 x 10^8 protons/pulse is produced. A PC board mounted switch internal to the module is used to select one of two values for $\hat{q}$ i.e., 3 pc/pulse or 30 pc/pulse. With this switch in the 30 pc/pulse position the resulting scale factor in the above example would be 1 x 10^9 protons/pulse.

OFFSET

Laboratory and preliminary field tests indicate that the offset is both very low and stable. A digitizer ($\hat{q}$ = 3 pc/pulse) and Gate Module (M = .829) have been operating successfully in the Neutrino beam line for the past few weeks. With the offset frequency on this unit adjusted to approximately 5 Hz, the count received during a beam off gate of 0.5 seconds was recorded for two periods of 3,763 and 1,780 machine cycles approximately one week apart. For both periods the beam off gate was 2 counts in over 85% of the cases and the difference in the mean value recorded for each period was 0.03 counts. Laboratory tests were conducted with the offset adjusted to 1 Hz out of the Digitizer on the 3 pc/pulse range which is equivalent to 3 pa of input current. During these test, the offset varied less than ± 0.5 Hz over a temperature range of $22^{\circ}C$ to $50^{\circ}C$. Note also that the Gate Module has the effect of further reducing the offset.

At present the input offset current is derived from a 1000 MΩ resistor connected from the input to ground. Thus, the input offset voltage of the input stage which is set to + 2.6 mv on one of the modules built produced 2.6 pa making up the major portion of the 3 pa equivalent input offset current. Hence, when the Digitizer is used in the 30 pc/pulse mode, the 3 pa of input current produces a 0.1 Hz offset frequency. This is extremely low and in fact presents a problem trying to remotely observe the offset. Increasing the offset frequency to 1 Hz in the 30 pc/pulse mode is not workable with the present circuit design. LED's on the Digitizer and the Gate Module indicate that a pulse is output from each of them respectively. Hence, the blinking LED's when no beam is present indicate that the offset is positive. One method of remotely determining if the offset is positive especially in the 30 pc/pulse mode is to feed the unscaled, ungated output from the Digitizer into an additional scaler channel which continues to count the offset frequency during the portion of the machine cycle when no beam is present. This has been done in the Proton East beam line where a Digitizer ($\hat{q}$ = 30 pc/pulse) and Gate Module (M = .485) have been operating for the past few weeks during which time the offset has never been observed to be much different than 0.1 Hz.

Although it is desirable to have low offsets, it is mandatory to have positive offsets which are stable. Since the Digitizer can only digitize negative current, if the net input current ever does go positive, the output frequency will go to zero resulting in positive charge being stored in the module. The subsequent application of a negative current must first remove the stored positive charge before pulses will be output. Whether or not the offset can realistically be maintained to below 1 Hz over long periods with a number of modules still remains to be seen. In addition, the effect of varying leakage currents from the SEM and/or cabling has not been fully investigated at this time, however, it is felt that compensating for them within the module should it be necessary, will not be a problem because of the digital nature of the output. In any event, it is believed that lower and more stable offsets can be achieved with a current digitizer than with conventional analog integrators.

CURRENT RANGE AND ACCURACY

The graph in Figure (2) is a plot of frequency error vs. input current from 5 pa to 100 na with a $\hat{q}$ of 3 pc/pulse for various temperatures in the range of 24°C to 53.2°C. A similar graph in Figure (3) is plotted for $\hat{q}$ of 30 pc/pulse from 50 pa to 1μa. It can be seen that the maximum error over the entire current and temperature range is ±1% limited at low currents by the offset frequency. At higher currents the Digitizer is limited for the most part by the output frequency (fo). Hence, the upper current limit is dependent upon $\hat{q}$ i.e., $I_{in} = \hat{q}$ fo. The ultimate frequency of the Digitizer with some degradation of accuracy is set at 150 KHz (450na) and 100 KHz (3μa) on the 3 pc/pulse and 30 pc/pulse ranges, respectively. At room temperature the accuracy is within ±1% up to 80KHz on both ranges.

To relate the input current to beam intesnity, the gain of the SEM must be known. The range of SEM gains observed have been from 3.62 pc/10^8 particles to 8 pc/10^8 particles. Hence, 10^{13} protons per second (PPS) can produce anywhere from 362 na to 800 na. The upper limit on beam intensity would be:

$$PPS_{max} = fo_{max} \times \hat{q}/S.G.$$

For, fo max = 80 KHz

$\hat{q}$ = 3pc/pulse

and S. G. = 8 pc/10^8 particles (worst case for PPS_{max})

$$PPS_{max} = 3 \times 10^{12} \text{ particles/sec.}$$

This of course assumes that it is desired to use a standard $\hat{q}$ in which case the scale factor in the above example from the Digitizer alone would be $\hat{q}$/S.G. = .375 x 10^8 particles/pulse. However, using the Gate Module with M = .375 would raise the scale factor to 1 x 10^8 particles/pulse i.e., 80,000 pulses into the module would produce 30,000 output pulses equivalent to 3 x 10^{12} particles.

INPUT FILTER

A low pass filter similar to that being used in present integrators is also used in the Digitizer. The purpose of the filter is to store charge produced by transients so as not to exceed the digitizing rate of the Digitizer as well as to reduce the effect of noise produced by the ground loop caused by grounding both the SEM and the Digitizer. The filter is a simple low pass filter with a 10 ms time constant (τ) which results in the overall transfer function of the Digitizer using Laplace notation being

$$\frac{Fo}{I_{in}} = \frac{1}{\hat{q}} \times \frac{1}{1 + s\tau}$$

Hence, an error can be produced when using a real time gate as we are interested in the total number of counts accumulated. In slow spill applications with gate times of 1 second or more, completely ignoring the effect of the filter will produce an error of less than -1%. It should be noted that this filter is not peculiar to the Digitizer and need not be that large for its proper operations. The 0.01 sec. time constant presently being used was selected on the basis of reducing the effect of 60 Hz noise observed in present SEM installations.

ON LINE TEST FEATURES

A push button on the front of the Digitizer (TEST) applies 3 na to its input which produces 1000 Hz (100 Hz) when $\hat{q}$ = 3pc/pulse (30 pc/pulse). The Gate Module also has a push button called UNITY which removes the multiplying feature i.e., sets M = 1.0. With one or both buttons depressed the Gate Module, should produce M x 1000 Hz (M x 100 Hz). Therefore, with appropriate gate times, it will be possible to determine if the system is operating properly. Provisions have been made to remotely make each of these tests, but this should be implemented with caution since the 3 na of test current will be added to any signal current.

SIGNAL DISTRIBUTION

The obvious interface to the MAC Control System is a Jorway scaler. Although the scaler can be displayed at any console, it is somewhat more difficult to physically obtain the data. The present Fermilab control system is capable of distributing such data via the 032 Serial Memory Buffer. However, this requires that the recipient of the data have a computer and program it to interface with the 032. Since some experimenters are reluctant to do this and other areas such as the Operations Center and the Main Control Room do not have computers for this purpose, an alternative method of distributing the data was sought. The present method of distributing SEM data is the 040 pulse train modules which can only be used in conjunction with A/D channels. Therefore, a counter and D/A converter was added to the Gate Module in order to obtain an analog voltage so that signals can be distributed using the 040 pulse trains as is presently being done with analog integrators.

SUMMARY

Analog integrators have long been used with Secondary Emission Monitors (SEM'S) to monitor beam intensity. The offset problems associated with these integrators stem from gating of low level currents and resetting of the integrators. Furthermore, the method of obtaining a standard scale

factor (1×10^8 protons/count) was to tailor a given integrator to a given SEM thereby causing a spare parts problem. A Current Digitizer which produces an output frequency proportional to input current has been developed which allows trivial digital techniques to be used in gating, resetting, and integrating of SEM currents for which the offset can be maintained to below 1 Hz. A second module called the Gate Module has also been developed which digitally scales the output frequency of the Digitizer to permit standardization of components. The Current Digitizer and Gate Module described are capable of monitoring beam intensities with various SEM'S up to 3×10^{12} protons/second with a scale factor of 1×10^8 proton/count, on one range and up to 3×10^{13} protons/second, with a scale factor of 1×10^9 protons/count on another range to within an accuracy of ±1% excluding the accuracy of the SEM calibration.

ACKNOWLEDGEMENT

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CURRENT DIGITIZER SPECIFICATIONS

	3 pc/pulse	30 pc/pulse
Input Current Polarity	Neg.	*
Max Digitizing Rate		
Initial	> 80 kHz	*
$22^{o}C < Ta < 50^{o}C$	> 33 kHz	*
Abs. max w/degraded accuracy (note 3)	>150 kHz	> 100 kHz
Input Current Range		
Initial	0 to 240 na	0 to 2.4 μa
$22^{o}C < Ta < 50^{o}C$	0 to 100 na	0 to 1μa
Abs. max w/degraded accuracy (note 3)	0 to 450 na	0 to 3.0 μa
Output Offset		
Initial	1 Hz	0.1Hz
$22^{o}C < Ta < 50^{o}C$	± .5Hz	± 0.05Hz
Accuracy (incl. offset)		
Absolute (Note 5)	± 1%	*
Relative $22^{o} < Ta < 50^{o}C$	± 1% + 1Hz ± .5Hz	± 1% ± 0.5Hz
Low Pass Input Filter		
Time Constant (Note 6)	10 ms	*
Max Frequency Error After 50 ms	- 1%	*
Max Count Error After 1 sec.	- 1%	*
Digital Outputs		
TTL	+ 5V pulse, 4μs long into 50Ω	*
NIM	- 2V pulse, 4μs long into 50Ω	*
Test Push Button (I_{in} = 3na)		
Initial	1000 Hz	100 Hz
$22^{o}C < Ta < 50^{o}C$	1000 Hz ± 12 Hz	100 Hz ± 1 Hz
Led Pulse Out Indicator	.1 sec., retriggerable	*

Note 1: * Indicates specification is the same as for 3 pc/pulse.
Note 2: Ambient temperature Ta @ + $25^{o}C$ unless otherwise specified.
Note 3: Degraded accuracy of ± 10% and ± 1.2% on 3 pc/uplse and 30 pc/pulse range, respectively.
Note 4: Within accuracy of ± 1% + 1 Hz ± .5Hz unless otherwise specified.
Note 5: Limited by calibration method.
Note 6: Not considering capacitance of input cable.

GATE MODULE SPECIFICATIONS

Pulse Input	Pos. TTL
Gating	2 independent gates Hi and Lo intended for Flat Top and Front Porch, respectively
Open	Pos TTL to R/I (Reset/Integrate) input, LED goes GREEN
Close	Pos. TTL to HLD (Hold) input, LED goes RED
Pulse Output (gated)	$f_o = MF_{in}$, $N_O = M\ N_{in}$
TTL	+5V pulse into 50Ω, variable length
NIM	-1V pulse into 50Ω, variable length
LED Pulse Out Indicator (Note 1).	.1 sec., retriggerable (ungated)
Scaler Reset Output	2 independent $\overline{\text{TTL}}$ (1μs, open collector) outputs derived from R/I pulse of each gate available to reset a Jorway scaler.
Scaling	M selectable from rear of module, .001 < M < .999
Freq. error - Hz (Note 1)	± 2.5/T max (± 1.5/T typ.), where T = gate open time.
Count error (Note 2)	± 2.5 max (± 1.5 typ.)
Unity Push Button	Sets M = 1.0
Analog Output	
Internal counter and D/A converter	Input derived from counting gated and scaled output pulses from both Hi and Lo gates, reset to zero with each Hi and Lo R/I pulse.
Range	0 to + 10V
Resolution	1 count = 1 mv
Accuracy (Note 3)	± 2 mv
Max LED Indicator	Indicates D/A is out of range, count of 9,999 is held until reset with R/I pulse.

Note 1: Period of output pulse train is not uniform
Note 2: After initialization which occurs with each R/I pulse
Note 3: Estimated from commercial specification

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ENGINEERING NOTE

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SUBJECT: FIGURE (1) - BLOCK DIAGRAM OF CURRENT DIGITIZER & GATE MODULE

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DATE: 5/3/78

REVISION DATE

n_p = NUMBER OF PROTONS

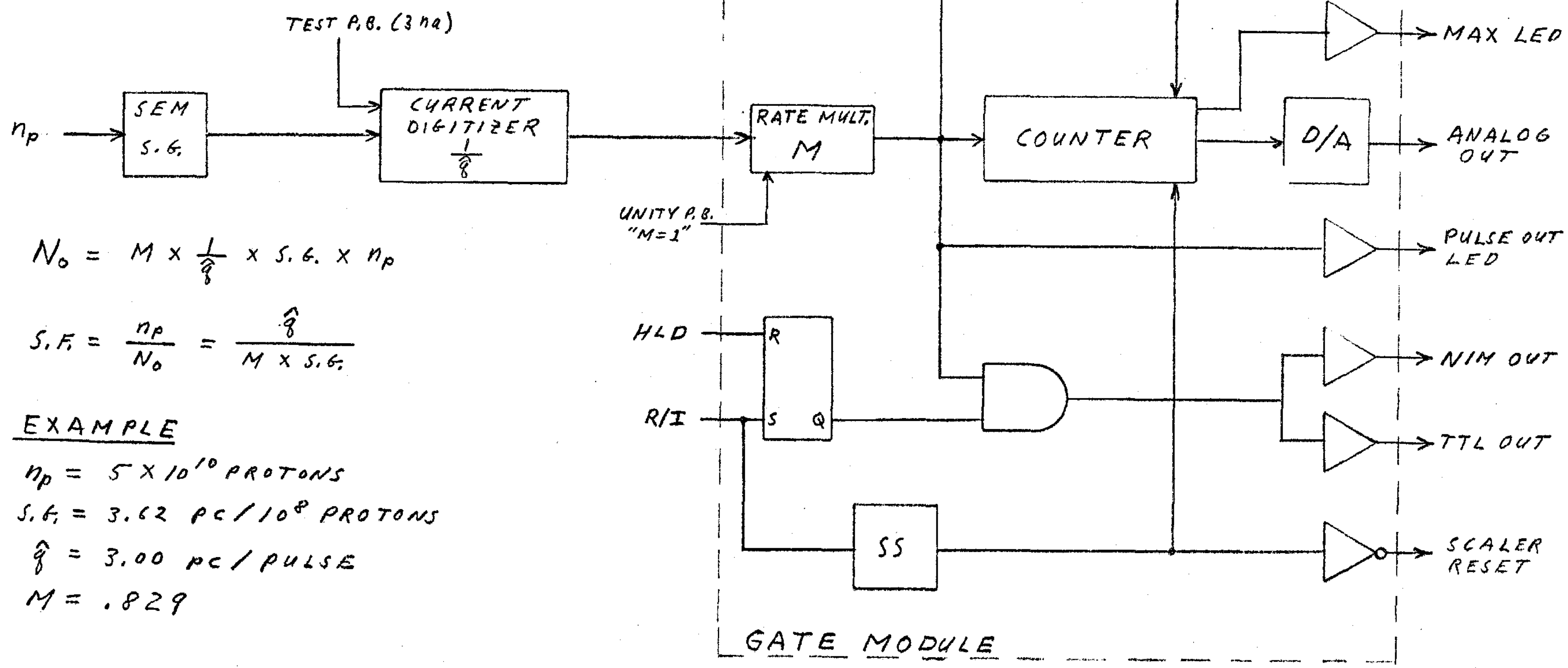
S.G. = SEM GAIN — pc / 10^8 PROTONS

$\hat{q}$ = UNIT CHARGE PER PULSE — pc/PULSE

M = MULTIPLIER

N_0 = NUMBER OF OUTPUT PULSES

S.F. = SCALE FACTOR



$$N_0 = M \times \frac{1}{\hat{q}} \times S.G. \times n_p$$

$$S.F. = \frac{n_p}{N_0} = \frac{\hat{q}}{M \times S.G.}$$

EXAMPLE

$n_p = 5 \times 10^{10}$ PROTONS

$S.G. = 3.62$ pc / 10^8 PROTONS

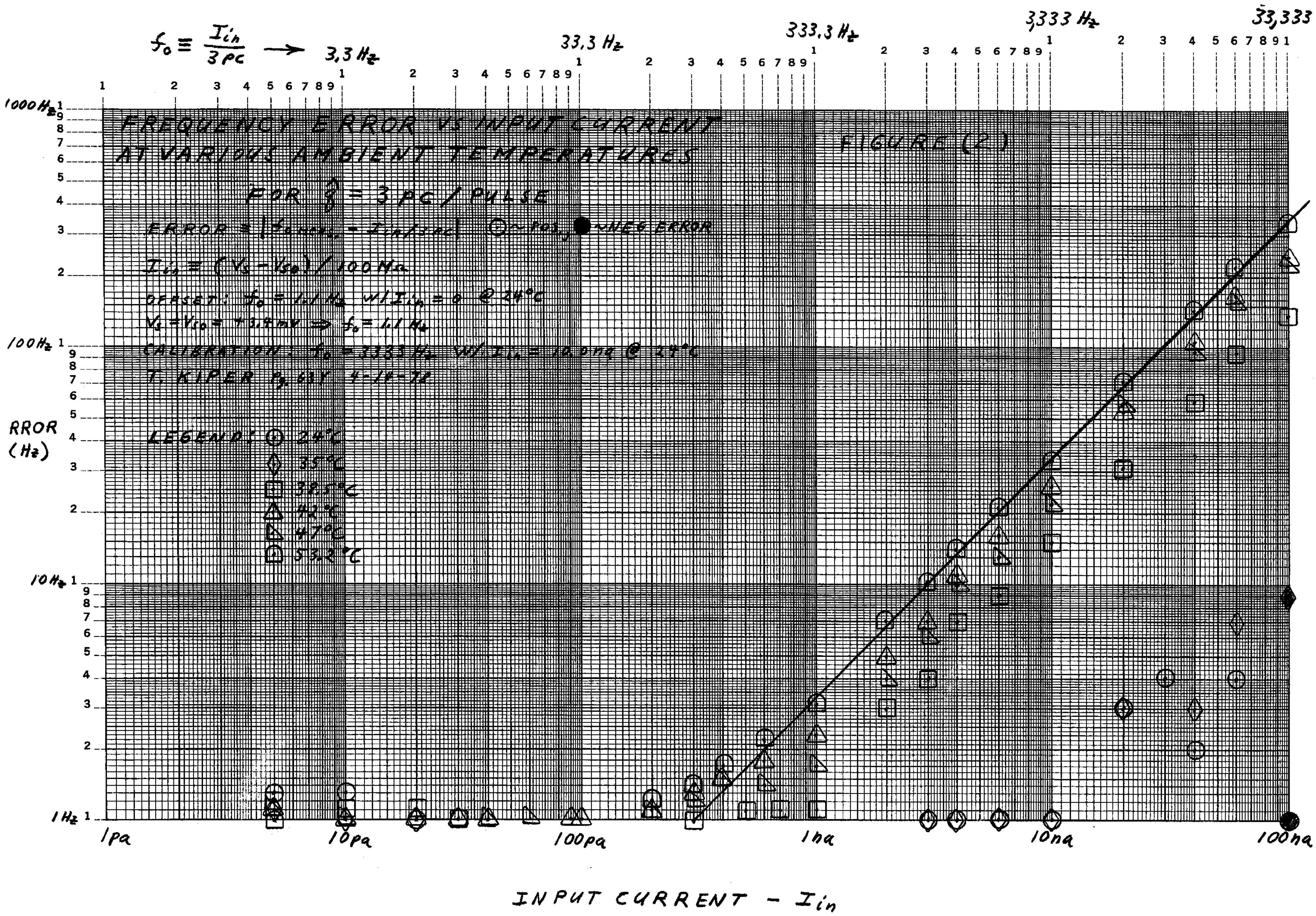
$\hat{q} = 3.00$ pc / PULSE

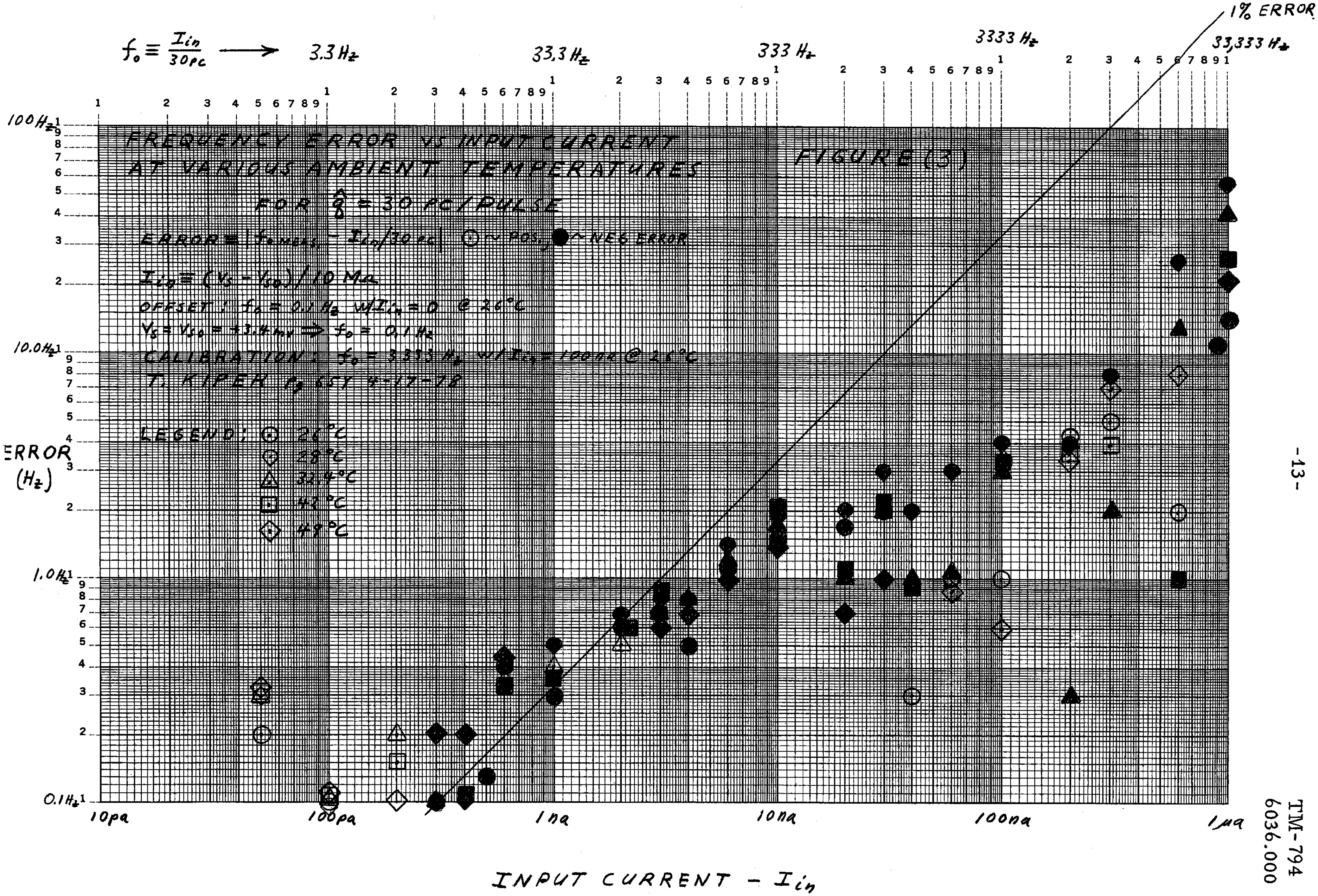
$M = .829$

$$N_0 = \frac{.829 \times 3.62 \text{ pc}/10^8 \text{ PROTONS} \times 5 \times 10^{10} \text{ PROTONS}}{3.00 \text{ pc / PULSE}} = 500 \text{ PULSES}$$

$$S.F. = \frac{3.00 \text{ pc/PULSE}}{.829 \times 3.62 \text{ pc}/10^8 \text{ PROTONS}} = .9997 \times 10^8 \text{ PROTONS/PULSE}$$

FIGURE (1)


FREQUENCY ERROR VS INPUT CURRENT
AT VARIOUS AMBIENT TEMPERATURES
FIGURE (2)
FOR q = 3 PC / PULSE
~ POS, ~ NEG ERROR
I_in ≡ (V_s − V_s0) / 100 MΩ
OFFSET: f_0 = 1.1 Hz W/ I_in = 0 @ 24°C
V_s = V_s0 = +3.4 mV ⇒ f_0 = 1.1 Hz
CALIBRATION: f_0 = 3333 Hz W/ I_in = 10.0 na @ 24°C
T. KIPER
4-14-72
LEGEND:
24°C
35°C
38.5°C
42°C
47°C
53.2°C
f_0 ≡ I_in / 3 pc → 3,3 Hz
33,3 Hz
333,3 Hz
3,333 Hz
33,333 Hz
1 % ERROR
1000 Hz
100 Hz
10 Hz
1 Hz
RROR (Hz)
1pa
10pa
100pa
1na
10na
100na
INPUT CURRENT − I_in


FREQUENCY ERROR VS INPUT CURRENT
AT VARIOUS AMBIENT TEMPERATURES
FIGURE (3)
FOR $\hat{q}$ = 30 PC/PULSE
ERROR ≡ $|f_{o\,MEAS.} - I_{in}/30\,pc|$ ⊙ ~ POS., ● ~ NEG ERROR
$I_{in} \equiv (V_S - V_{S0})/10\,M\Omega$
OFFSET: f_o = 0.1 Hz W/I_{in} = 0 @ 26°C
$V_S = V_{S0}$ = 43.4 mv ⟹ f_o = 0.1 Hz
CALIBRATION: f_o = 3333 Hz W/I_{in} = 100na @ 26°C
T. KIPER Rg 6SY 4-17-78
LEGEND: 26°C
28°C
32.4°C
42°C
49°C
$f_o \equiv \frac{I_{in}}{30\,pc}$ ⟶ 3.3 Hz
33.3 Hz
333 Hz
3333 Hz
33,333 Hz
1% ERROR
ERROR (Hz)
100 Hz
10.0 Hz
1.0 Hz
0.1 Hz
10pa
100pa
1na
10na
100na
1μa
INPUT CURRENT – I_{in}